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EXPERIMENTS WITH A SPHERE FROM WHICH THE BOUNDARY LAYER IS REMOVED BY SUCTION

By Oskar Schrenk

From "Zeitschrift für Flugtechnik und Motorluftschiffahrt,"
September 14, 1926

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EXPERIMENTS WITH A SPHERE FROM WHICH THE BOUNDARY LAYER IS REMOVED BY SUCTION.*

By Oskar Schrenk.

The task of removing the boundary layer by suction consists in producing, in place of the ordinary flow with the formation of vortices, another kind of flow in which the vortices are eliminated by drawing small quantities of fluid from certain points on the surface into the interior of the body.

This idea is an outgrowth of the boundary-layer theory and is nearly as old as the theory itself. When Professor Prandtl made the first public announcement in 1904, regarding his boundary-layer theory, he referred to an experiment he had made for confirming his theoretical conclusions, which experiment was based on the suction principle. It was only at a much later date, however, that the hope of opening up new technical possibilities with the aid of suction furnished the incentive to more thorough researches in this field. These researches have been carried on since 1922 by J. Ackeret and A. Betz in the Göttingen Aerodynamic Laboratory, and have led to some very good results, which, however, for various reasons it has hitherto been impossi-

* "Versuche an einer Kugel mit Grenzschichtabsaugung," from "Zeitschrift für Flugtechnik und Motorluftschiffahrt," September 14, 1926, pp. 366-372.

ble to publish.*

The experiments with a sphere, which constitute the subject of this report, were made early in the present year with apparatus which had been previously used by Ackeret.

I. Theoretical Considerations

In order to understand what is to follow, it is first necessary to consider certain aspects of the boundary-layer theory.**

It is customary to designate as "boundary layer" the usually quite thin layer of fluid along the surface of a body, in which the velocity, under the influence of viscosity, is reduced from its full value to zero at the wall (Fig. 1). Outside of this layer, there prevails the so-called "potential flow," in which practically no viscosity effect can be traced. This dual division of the stream into viscous boundary layer and non-viscous potential flow is a simplifying assumption for a chiefly

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* Excepting a brief report on "Experiments with an Airfoil from which the Boundary Layer is Removed by Suction" (See N.A.C.A. Technical Memorandum No. 374, by J. Ackeret, A. Betz, and O. Schrenk), in No.4 of "Vorlaufige Mitteilungen der Aerodynamischen Versuchsanstalt zu Gottingen."

** The reader is here referred to several articles which deal with boundary-layer phenomena in connection with slotted wings and the Magnus effect: Ackeret, "Recent Experiments at the Gottingen Aerodynamic Institute," "Zeitschrift für Flugtechnik und Motorluftschiffahrt," Feb. 14, 1925, pp. 44-52 (N.A.C.A. Technical Memorandum No. 323); Betz, "Berichte der Wissenschaftlichen Gesellschaft für Luftfahrt," No.6, Jan. 1922; Betz, "Magnus Effect, the Principle of the Flettner Rotor," "Zeitschrift des Vereines deutscher Ingenieure," Jan. 3, 1925, pp. 9-14 (N.A.C.A. Technical Memorandum No. 310); Prandtl, "Application of Magnus Effect to Wind Propulsion of Ships," "Die Naturvissenschaften," 1925, pp. 93-108, (N.A.C.A. Technical Memorandum No. 367).

rapid but constant fading away of the viscosity effect from the wall outward. In the potential flow, as distinguished from the boundary layer, we have the so-called law of Bernoulli, $p + \frac{\rho}{2} w^2 = k$, which clearly connects the pressure p of any point with its velocity. In this connection ρ (the density of the fluid in question) is to be regarded as constant, while the value of k is the same for the whole potential flow.

Within the boundary layer the air can flow along the wall in smooth parallel layers, in which case the boundary layer is designated as "laminar." This parallel flow may, however, overlay an irregular vortical mixed flow, in which case the boundary layer is called "turbulent." The latter form of flow usually occurs when the so-called "Reynolds Number" of the boundary layer in question, $\frac{u \delta}{\nu}$ (in which u = the undisturbed velocity at the edge of the boundary layer, δ = the thickness of the boundary layer and ν = the kinetic viscosity of the fluid), exceeds a certain critical value. Below this value the laminar flow is stable. It may be added that, in bodies of geometrically similar shape, the transition from the laminar to the turbulent flow in the boundary layer is simply a function of the Reynolds Number of the body $\frac{v l}{\nu}$, as usually defined (v = velocity of flow, l = a definite reference length on the body). A further important distinction can be made between the two kinds of flow. In the turbulent boundary layer with its mixed flow, there is a much more vigorous lateral transference of force than in the

laminar flow, where the impulses are transmitted between parallel layers by the forces of viscosity alone. This fact may be explained by assuming that the "microscopic" mass and impulse exchange of the mixed flow is added to the molecular or "microscopic" mass and impulse exchange of the viscosity. This explains the fact that the velocity in the turbulent boundary layer is still quite high near the wall and finally drops abruptly to zero, in contradistinction to the laminar boundary layer, in which the velocity decrease is much more gradual.

The boundary layer often emerges from its "invisible" state and suddenly produces turbulent regions on the rear side of objects or behind sharp edges. These turbulent regions push away the smooth potential flow from the surfaces and cause the well-known phenomenon of separation or detachment. The turbulent regions are filled with much-retarded and eddying and often backward-flowing air, which, as the distance from the object increases, gradually recombines with the outer potential flow by diffusion and friction. It can also be established that the region where detachment threatens is always where the potential flow has been retarded.

Since the boundary layer is the cause of this detachment, it has also been experimentally investigated. Motion pictures of running water show that, in the first moments of motion around a cylinder, there is a potential flow, devoid of turbulence, which combines on the rear side of the cylinder in a center of

dynamic pressure, just as it separates on the front side.* It is then seen that, behind the place of maximum cylinder width and hence in the region of retarded flow, a disturbance suddenly develops from the boundary layer, which finally transforms the whole flow into a region of turbulence or "dead water."

This disturbance is caused by the stopping and the partial return flow of the boundary-layer material. That which takes place in the boundary layer at this instant is, to a certain degree, physically comparable with the motion of a pendulum retarded by friction, while the potential flow corresponds to a frictionless or ideal pendulum. A pendulum can be released without initial velocity from its starting altitude and will move toward the lowest point of its path. This corresponds to the beginning of the boundary-layer flow at the forward center of pressure, i.e., at the center of maximum static pressure with the velocity zero. If the pendulum were not affected by friction, it would, at this point, have acquired just as much kinetic energy as it had lost potential energy (point of maximum condensation of the streamlines and hence, according to Bernoulli's law, the point of maximum pressure in the potential flow). At the expense of the kinetic energy just acquired, the pendulum could then regain its original altitude at the opposite end of its path, which it would reach at exactly zero velocity (corresponding to complete regaining of the pressure in the potential flow at the expense of velocity). This process changes, however,

* Tietjens, 1925 Yearbook of the W.G.L., p. 100 ff. See also "Kinetographic Flow Pictures," by Prandtl and Tietjens, N.A.C.A. Technical Memorandum No. 364.

when the pendulum is retarded by friction. Since some of its energy is lost, it can not reach its original altitude, but stops short of it and thus loses potential energy.

In place of the tangential force components in the pendulum, the boundary layer has the pressure course which, on account of its thinness, is impressed upon it by the outer potential flow. Thus it is comprehensible that, after the first moments of flow along a surface, boundary-layer material may suddenly accumulate at any point of the pressure increase, may push out into the potential flow with partial return flow and may combine with portions of the latter in vortical forms, from which the turbulent region behind the body is evolved.

The portion of the boundary layer in contact with the wall is so greatly retarded that we might expect the reversion and detachment of the flow to begin here simultaneously with the setting in of the pressure increase. Many slender objects, however, show no real flow detachment in their region of pressure increase, but only a great retardation and extension of the boundary layer, which may, moreover, produce a change, even though slight, in the combined flow, as compared with the pure potential flow. The reason the detachment does not occur in such cases, is the previously mentioned lateral-impulse transmission, which is small for a laminar boundary layer, but may be quite large for a turbulent layer, and indicates a towing effect opposed to the slackening of the boundary-layer flow. This towing effect is also connected with the often-observed fact that the detachment

of the flow from bodies above the critical region begins farther back than below the critical region (Figs. 2-3).

In such dangerous regions of pressure increase, the removal of boundary-layer material by suction serves to prevent excessive thickening of the boundary layer and thereby the detachment of the flow at this point. In many cases a single narrow suction region is not sufficient, but several such strips must follow one another, or a surface must be used from which the boundary layer is continually removed by suction. Since the pressure relations round about a body are very closely connected with the course of the outer flow, suction is also a means for influencing the forces of pressure acting on a body, including the lift (and induced drag) and the pressure resistance produced independently of the lift. Any production or increase of dissymmetry in the flow about a body means an increase in the lift (including induced drag), a diminution of the turbulent region and a diminution of the pressure resistance produced by the displacement of the potential flow. It is known that the pressure resistance is zero for a potential flow without turbulence.

A further possibility, afforded by this suction, is the improvement of the flow in elbows, diffusers, etc. Regarding this point the reader is referred to an article on the removal of the boundary layer by suction, which is now being prepared by Ackeret and will be published in the "Zeitschrift des Vereines deutscher Ingenieure.

Regarding many dead-water formations (e.g., on sharp bends and edges) the opinion might be held that the detachment and straight-ahead flow is the natural form of flow resulting from inertia, that it has nothing to do with the boundary layer and could not therefore be prevented by suction. This view is incorrect. Even in these cases, the fluid forms no turbulent region at the very first. Both kinds of flow are, in a certain sense, physically conceivable, namely, the one free from turbulence and the one with a dividing surface between the fluid at rest and the fluid in motion. The production of such a dividing surface is impossible, however, in the acceleration of the matter from the condition of rest, as demonstrated by the consideration of the pressure relations.* Even in these cases, the detachment is caused by the boundary layer.

Important also is the establishment of the facts that the pure surface-friction drag is not diminished but augmented by the suction and that therefore the removal of the boundary layer from a body with predominant frictional resistance or drag is accompanied by no diminution of the drag.

A sphere was tested as an example of the effect of the suction, the special aim being to diminish the turbulence and conse-

* An acceleration of the fluid only on one side of a dividing surface would mean that here, in the first instant, a pressure decrease $\Delta p = \Delta \frac{1}{2} \rho \frac{dv}{dt}$ along the dividing surface, connected with the acceleration would occur, while this could not occur in the immediately adjoining, unaccelerated region. Pressure impulses would thus arise athwart the dividing surface, which is physically impossible.

quently the pressure resistance. How large, in the case of the sphere, the effect of the magnitude of the turbulent area can be on the pressure distribution, is shown by the consideration of the subcritical and supercritical flows about the sphere without suction (Figs. 2-3), for which the pressure-distribution data are available (Fig. 5). The computed pure potential flow, as it might be obtained through perfect removal of the boundary layer by suction, is added as the third case (Fig. 4). The three pressure distributions are represented by three different c_w values, the greatest for the laminar boundary-layer flow and $c_w = 0$ for the pure potential flow. The pressure distributions I and II are taken from Eiffel experiments, but seem to show some inaccuracies.* The problem of the critical numbers for spheres is thoroughly discussed elsewhere.**

II. Apparatus

The experiments were performed in the small wind tunnel at Göttingen. The drag was found in the usual manner by weighing (See "Ergebnisse der Aerodynamischen Versuchsanstalt zu Göttingen," Part I, p.27). The arrangement of the apparatus is shown in Fig. 6. The portion connected with the drag balance is suspended by the wires V_1, V_2, and D and consists of the

* Eiffel, "Nouvelles recherches sur la resistance de l'air et l'aviation," Paris, 1914, p.92.

** Prandtl, "Der Luftwiderstand von Kugeln," Nachrichten d. Kgl. Gesellschaft d. Wissenschaften zu Göttingen, Math.-Phys. Klasse 1914. Wieselsberger, "Der Luftwiderstand von Kugeln," "Zeitschrift für Flugtechnik und Motorluftschiffahrt," 1914, p.140.

sphere and the tubes as far as the vertical tube R. The drag balance is connected with the forward center of pressure by the wire W, which is kept taut by a weight Sp attached behind the sphere. The vertical tube R and the water tank Wg (Fig. 7) are located outside the air stream. It is apparent that the movable portion of the apparatus can swing freely during the weighing without interfering with the suction.

Inside of R there is a narrow-meshed sieve S_2, whose object is to straighten the air flow before it enters the fixed tube A, since otherwise an opposing force would be exerted on the suspended portion of the apparatus, thereby impairing the drag measurement. It is also important for the planes of V_1 and V_2 and the direction of D to be vertical, lest lifting forces on the sphere and streamlined tube likewise cause an error in the drag. Above all, such an error might be caused by the pressure on the upper end of R, resulting from the difference between the internal and external pressures.

Fig. 8 shows the suction apparatus inside the sphere, together with the dimensions. The sphere was turned out of wood and polished. In the first experiments, a plain woven-wire sieve was used as the surface for the suction region and subsequently a finely perforated brass sheet 0.4 mm (0.157 in.) thick (Fig. 9). The diameter of each hole was 0.3 mm (0.012 in.) and the number of holes was 108/cm² (696/sq.in.). The air was drawn away from annular strips, as shown in Fig. 8. The arrangement

shown here is the one used in the experiments of previous years. Since, at that time, the foremost strip was found to be superfluous (at least for the supercritical region with its point of detachment far to the rear), this strip was subsequently closed by a strip of ordinary tin. Furthermore, the other individual strips were replaced by a single spherical cap, on which suction rings and uncovered regions could be arranged by pasting thin paper.

Inside the sphere there was a device for measuring the negative pressure produced by the suction. This device consisted of a small brass tube, with lateral perforations, whose open rear end terminated inside the tube T of the suction pipe (Fig. 6). The rubber measuring tube, there located, was of course removed during the weighing.

The quantity of air flowing through the tube A was determined from the fall in pressure, according to Bernoulli's law, by means of the Venturi tube at M (Fig. 6). A wire-gauze sieve or strainer S_1 had to be placed in front of the Venturi tube, in order to produce a uniform velocity distribution. A honeycomb current rectifier H, also had to be inserted between the Venturi tube and the centrifugal fan, since the latter, in the requisite strongly throttled condition, caused rotating air currents to flow to the measuring point and thus increased the pressure reading at the circumference of the tube.

III. Experiments and Results

As already mentioned, the quantity and the negative pressure of the removed air and also the resistance were determined by measurement. It is known that the resistance measurements of the sphere, even under ordinary conditions, offer great technical difficulties. Things appearing at first of trifling importance, such as the degree of turbulence of the wind, slight superficial roughness and the method of suspension, sometimes greatly affect the course of the flow, the point of detachment and the resistance or drag. These difficulties are increased in the case of the sphere from which the boundary layer is removed by suction, where the character of the surface and the size of the suspension device are determined by other conditions. The annular strip of tin at the equator (the region of greatest sensitivity to disturbing influences) is, in this respect, somewhat questionable, as also the covering with paper, but they could not be avoided at first. It is not surprising therefore that the resistance or drag values of our sphere, when not subjected to suction, are not exactly the same at different times and that they do not entirely agree with previous resistance measurements with spheres.

The simultaneously measured secondary resistances (wires and tubes in the air stream) were eliminated by auxiliary experiments. They can not be determined with absolute accuracy, because the flow behind the sphere, where these parts are mostly

located, differs for every case. An auxiliary experiment was tried without suction with the sphere suspended only as a screen before the parts producing the secondary resistances. Another experiment was tried for the case with suction, in which the sphere was removed, thus leaving the parts producing the secondary resistances in the unimpeded air stream. In a potential flow without any turbulent region the second auxiliary experiment alone would have given approximately correct results. The actual relations seem to be closely approximated by the arithmetical mean between the first and second determinations of the secondary resistances or drags. An estimation indicated a possible error of about ±5% in the resistance of the sphere by this calculation method.

The object of the experiments was to determine the greatest possible resistance diminution in our experiment apparatus. They were not therefore very systematic. In every case the suction was as great as the fan could produce, since it was found that an increase in the resistance always accompanied any diminution in the suction. The effect of the suction is therefore always approximately, though not exactly, the same. The manner of presentation of the results in Figs. 10-11 was necessitated by this method of experimentation. Regarding the wind velocity v and the corresponding Reynolds Number $R = \frac{vd}{\nu}$ (d = diameter of sphere) for every kind of uncovering, there are here plotted: c_{wo}, the drag coefficient of the sphere without suction; c_w,

the best coefficient obtained by suction; and the nondimensional coefficients x and z, from which the strength of the suction can be calculated.

The quantity of air sucked away per second is determined from x,

$$Q = x\ v\ F$$

and the suction strength from z:

$$L = z \frac{\rho}{2} v^3 F, \quad \text{in which} \quad F = \frac{d^2 \pi}{4}.$$

xF can be conceived as a surface which gives an optical presentation of the quantity of air removed by suction. Within a cylinder consisting of streamlines and having a cross section xF, all the air drawn in flows toward the sphere (this cross-sectional area is, in our experiments, 1-7% of the total cross-sectional area F).

$L_a = Qp_a$ was taken as the force of the suction (p_a = the negative pressure inside the sphere). The force thus defined is only the force required to draw the air into the sphere. The force required to remove the air from the sphere depends on the arrangement and is not here taken into account.

The results show considerable diminution in the drag, which is especially noticeable in the medium velocities. An equal drag diminution, with corresponding suction effects, can naturally be expected for higher velocities. Our small fan is not powerful enough here. The increase in the drag at low velocities, in the subcritical region of our sphere, has another cause

(the critical Reynolds Number of our sphere is about 200,000). The previously mentioned closing of the equatorial suction strip probably produces an unfavorable effect here. Even before the suction begins, the potential flow in the subcritical case becomes detached, near the equator (Fig. 2), and what must now be drawn in additionally, in order to restore the potential flow, is not only the boundary-layer material, but a large quantity of previously free-flowing air which, after the detachment, has become mixed with the boundary layer in the formation of vortices. The forward impulse of all these quantities of air reduced to zero velocity shows in the balance as drag.

The suction quantities and forces are strikingly large, being much larger than rough theoretical calculations would lead us to expect. This fact can probably be explained by the character of our experimental apparatus. This could not be changed, however, during the present series of experiments, since such changes would require considerable time and money. The large quantity of air withdrawn by suction is probably due to excessive superficial roughness with relation to the thickness of the boundary layer. The latter is thin (about 1 mm = 0.04 in.) and the portion sucked away is considerably thinner. A great deal seems to depend on the smoothness of the body. The great negative pressure, required to produce the suction, is due to the insufficient perviousness of the sieve, which was originally designed for small quantities. The experiments showed that in the

cases of small c_w values, the internal negative pressure produced by the suction was from two to six times the dynamic pressure $\frac{\rho}{2} v^2$, while the external negative pressure on the portion of the sphere subjected to suction was between zero and $0.7 \frac{\rho}{2} v^2$. All the remaining pressure in the cases tested, hence 2/3 to 11/12 of the total pressure, was required to overcome the resistance of the sieve, which was all the greater because the entrance velocities through the different suction strips usually differed from one another. It is obvious, however, that the reduction of the quantity of air sucked away and the increase in the effect of the suction to that theoretically possible is indeed conceivable and to be expected, but requires further experimentation.

Figs. 12-13 show the diminution of the turbulent region by the aid of suction. The smoke introduced from the rear shows the extension of both turbulent regions, Fig. 12 being obtained without and Fig. 13 with suction. Fig. 13 shows very clearly how unstable the potential flow, produced by the suction, can be. The portions of the smoke, which have passed farther away from the sphere, lie considerably higher than the turbulent region at the instant of its inception on the sphere. The turbulent region is therefore deflected during the preceding instant from above downward. Similar oscillations were constantly traceable even in measuring the negative pressures and the quantities of air, as also in finding the drag. There were cases where simultaneous measurements of the drag and of the negative pressure

showed oscillations between two essentially different states of flow, which took place at intervals of several seconds. This question of stability naturally plays a more important role in more technical problems than it does here.

As a sort of appendix, we will present still another consideration, which likewise concerns a more technical aspect of the problem of reducing the resistance or drag by means of suction and which is not therefore of great importance for the case of the sphere, especially with the values of z and x thus far obtained.

For judging the possible saving in energy, as will be demonstrated, the power without suction is

$$L_o = c_{wo} \frac{\rho}{2} v^3 F$$

not simply opposite

$$L = c_w \frac{\rho}{2} v^3 F$$

but

$$L' = (c_w + z - x) \frac{\rho}{2} v^3 F,$$

in which $c_w + z - x$ is a sort of effective coefficient of drag in the suction case. Moreover, we have in its place, if we include the efficiency η of the suction fan,

$$c_w + \frac{z}{\eta} - \eta x.$$

The term z (or $\frac{z}{\eta}$) here means nothing more than the power required for sucking the air into the sphere. The other term

$-x$ (or $-\eta x$) is a little harder to understand, since it is involved with the manner of removing the air from the inside of the sphere. It is manifest that the method of our experiment, namely, to draw off the air laterally and perpendicularly to the direction of the wind, is not technically the best, when we consider that any thrusting back of the air toward the rear will always produce a forward thrust and is therefore better than any other method of removing the air. The problem is simply as to what is the best velocity for forcing the air toward the rear. This velocity is denoted by $n\,v$, in which n is a coefficient of unknown value at first. An accelerating force of

$$L_b = Q \frac{\rho}{2} n^2 v^2 = n^2 x \frac{\rho}{2} v^3 F$$

is required in order to raise the velocity of air in the sphere from 0 to this velocity. This force therefore corresponds to a nondimensional coefficient

$$c_w' = n^2 x.$$

According to the law of impulsion, the backward thrust produces a negative coefficient of drag

$$\Delta W = - Q \rho n v = - 2 x n \frac{\rho}{2} v^2 F$$

hence a nondimensional coefficient

$$c_w'' = - 2 x n.$$

The best exit velocity $n\,v$ is the one in which the minimum value of n is

$$c_w''' = c_w' + c_w'' = x\,n^2 - 2\,x\,n,$$

the reduction of which gives

$$n = 1.$$

The air is best removed therefore at its entrance velocity. c_w was determined in our experiment without any backward-thrust coefficient and, moreover, the acceleration force, as previously determined, was not measured simultaneously. The case of our experiment is therefore the one with $n = 0$ and hence, $c_w''' = 0$, while $c_w''' = -x$ corresponds to the best $n = 1$. We may therefore deduce this value x from the measured c_w, in order to obtain the most favorable case of the effective resistance or drag. This value x (taking into account the efficiency of the pump) finally becomes $\eta\,x$, as follows from the repetition of the minimum value for

$$c_w''' = \eta\,x\,n^2 - 2\,x\,n$$

instead of the earlier value $x\,n^2 - 2\,x\,n$. Moreover, the best exit velocity is here $\eta\,v$ instead of v.

If this result is applied to the experimental values, we find that

$$c_w + \frac{z}{\eta} - \eta\,x$$

in the most favorable cases, is approximately of the same magnitude as c_{wo} (e.g., for $v = 13$ m (43 ft.)/sec. on Fig. 11b: $c_{wo} = 1.3$ and $c_w + \frac{z}{\eta} - \eta\,x = 1.32$ with the assumption of

$\eta = 0.75$). This apparently rather poor result is due to the above-described suction conditions of our sphere and will be improved along with the experimental values for x and z.

Translation by Dwight M. Miner,
National Advisory Committee
for Aeronautics.

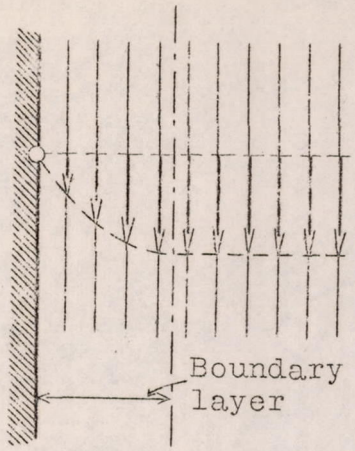


Fig.1

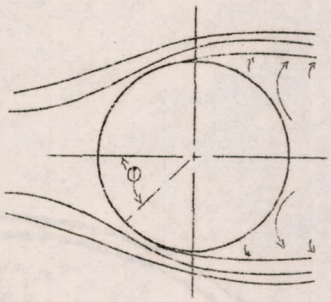


Fig.2 Subcritical flow.

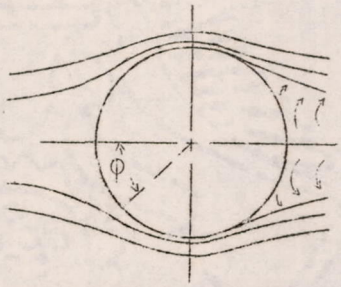


Fig.3 Supercritical flow.

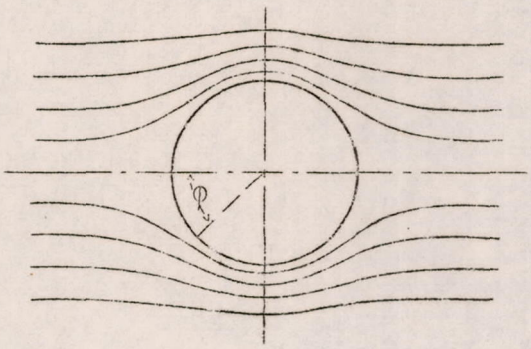


Fig.4 Theoretical potential flow.

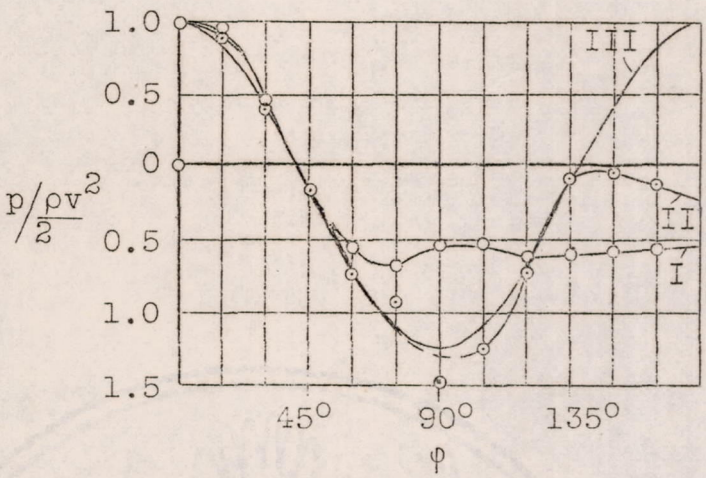


Fig.5 Pressure distribution in Figs.2-4: I for Fig.2; II for Fig.3; III for Fig.4.

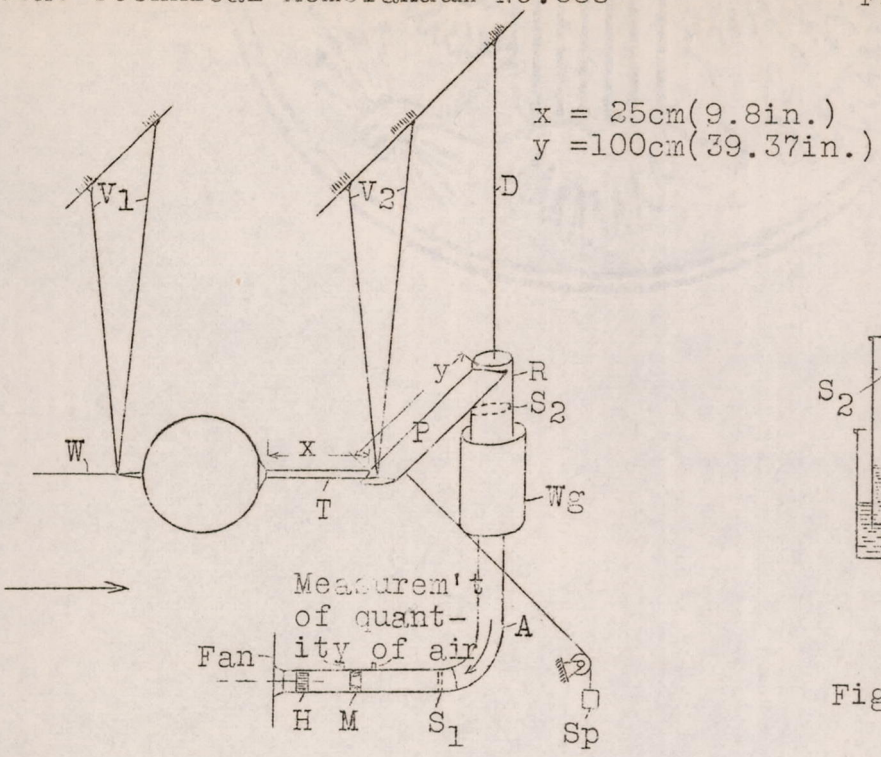


Fig.6

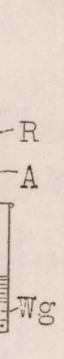


Fig.7

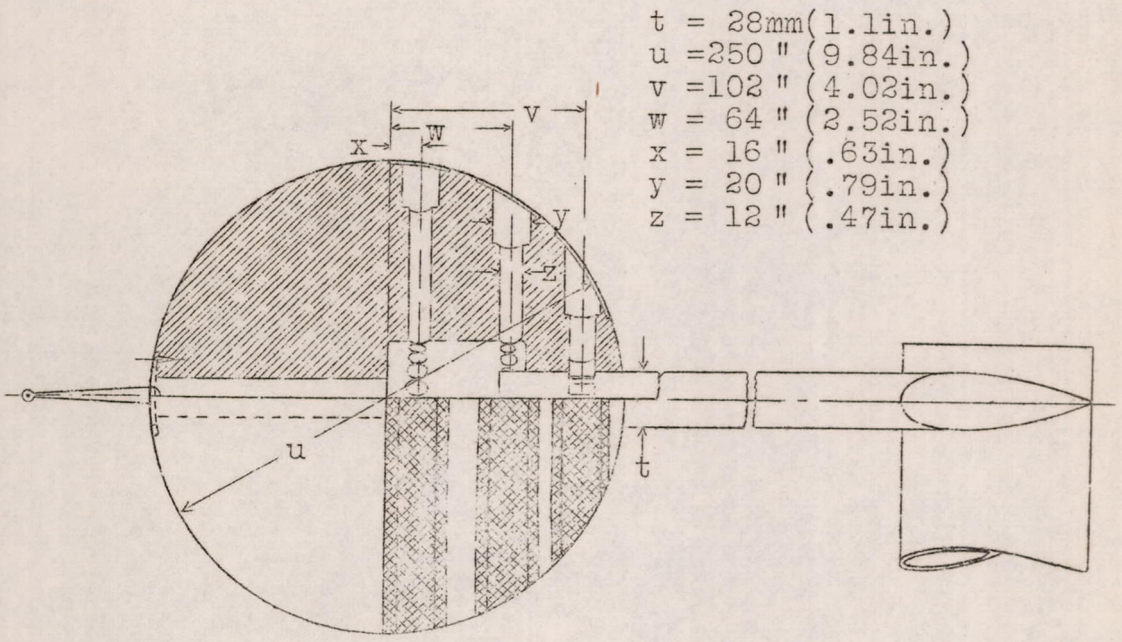
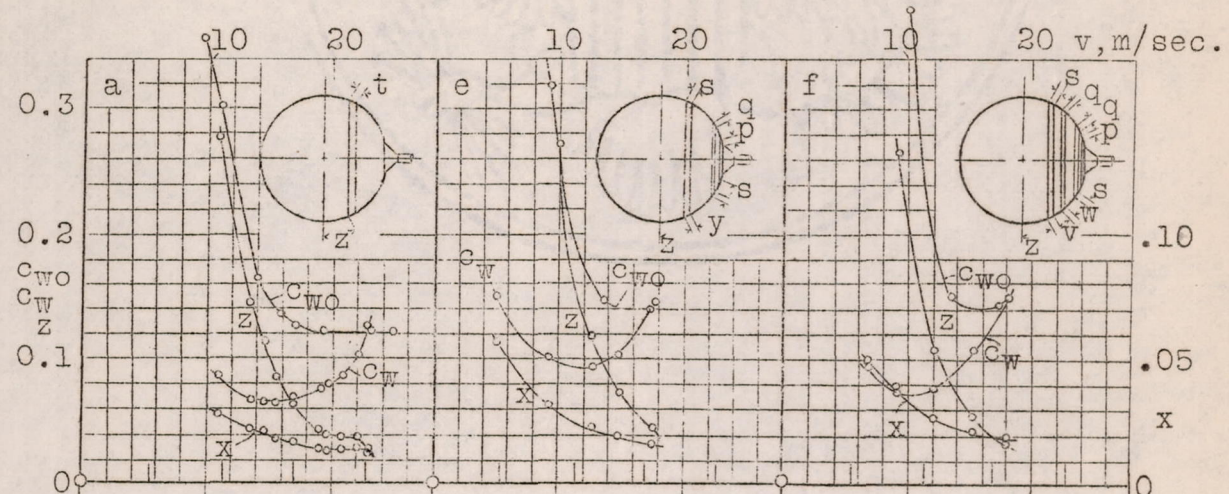


Fig.8 Sphere with devices for removing boundary layer by suction.



p = 4mm(0.157in.)
q = 5mm(0.197in.)
r = 7.5mm(0.295in.)
s = 10mm(0.394in.)
t = 12mm(0.472in.)
u = 15mm(0.591in.)

v = 23mm(0.906in.)
w = 25mm(0.984in.)
x = 35mm(1.378in.)
y = 45mm(1.772in.)
z = 55mm(2.165in.)

Fig.10

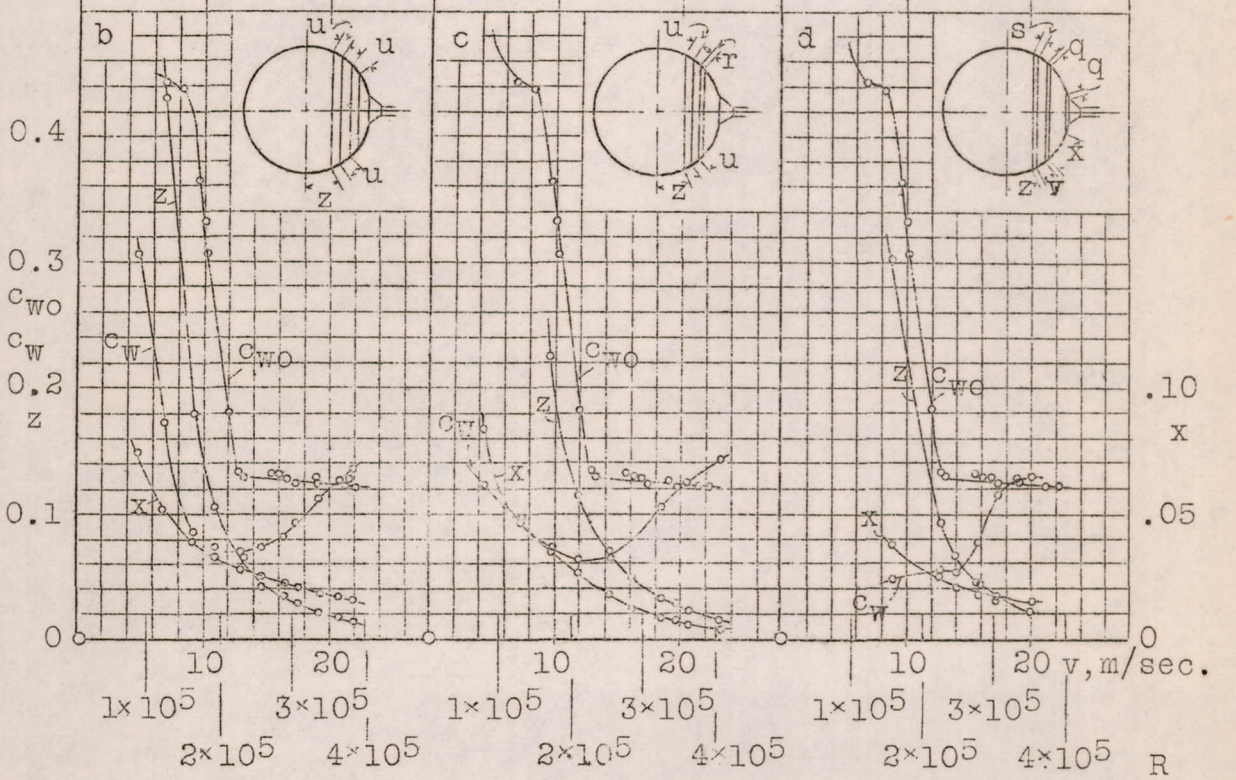


Fig.11

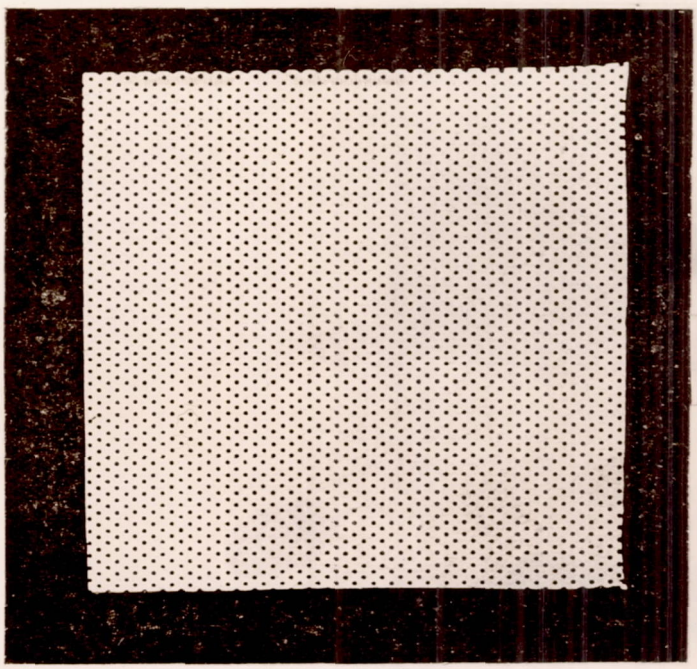


Fig.9

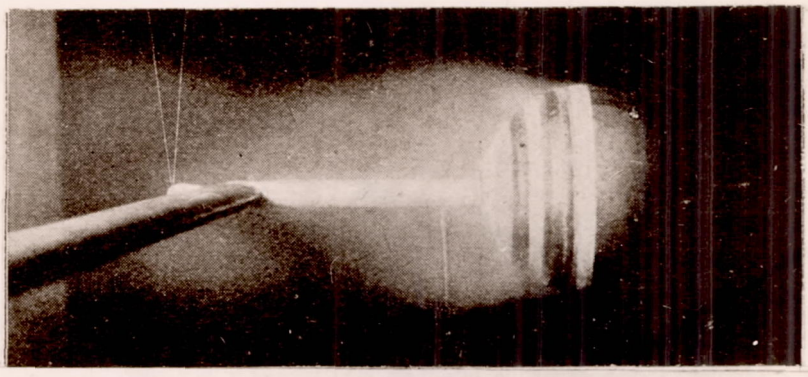


Fig.12 Turbulent region with suction

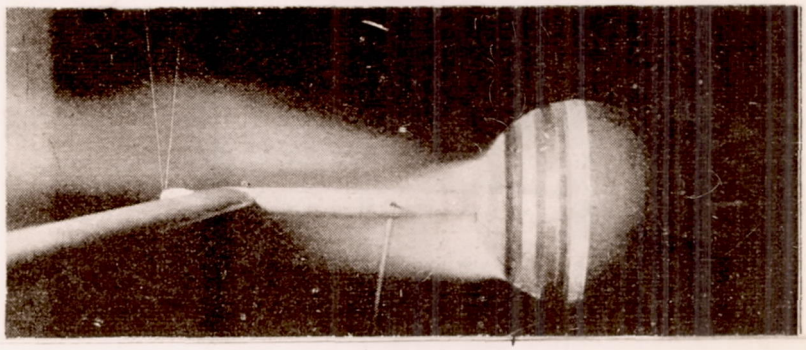


Fig.13 Turbulent region without suction